Reports

Military Uses of Uranium: Keeping the U.S. Energy Accounts

Abstract. *Present accounts of U.S. energy consumption are incomplete in two ways: they include neither the direct military uses of nuclear energy nor the mostly military, nonfuel uses of uranium. Preliminary estimates indicate that significant distortions are created in the data on U.S. nuclear energy consumption patterns as a result of these omissions.*

Important to the study of energy's value to society are accurate data about energy production and use categorized by sources, economic sectors, and time. Although there are minor variations in the basic information sources and the accounting procedures for cogeneration and hydropower differ slightly, data of this sort are usually considered to be complete for the United States in recent years. However, in two important respects the normal presentation of this information is not complete or consistent: (i) it does not include military uses of nuclear energy and (ii) it treats the nuclear fuel cycle differently from other fuel cycles. The first of these problems can be resolved if one examines the military's historical use of nuclear energy, but the second requires that one choose an appropriate denominator for the efficiency equation, one that will represent the energy contained in mined uranium.

In most charts of U.S. energy production, nuclear power barely appears until the early 1970's and then as only a small fraction of the total energy production (*1, 2*). These figures are based on the amount of thermal energy produced in commercial power plants. The military uses of nuclear energy in nuclear detonations and reactors are not included, even though military uses of other fuels have been included. The details of the bomb yields and power levels of military reactors are generally classified, but estimates have been made that will allow a preliminary accounting.

Table 1, compiled from various sources, lists the major uses of military nuclear energy—plutonium production reactors, naval propulsion reactors, and nuclear (and thermonuclear) detonations. The data for commercial power plants (last column) are normally presented as the entire nuclear contribution (*2*). This tabulation illustrates that the installed civilian reactor capacity did not exceed the military capacity until about 1970 and that the cumulative civilian nuclear production did not exceed the military production until about 1975.

There are three independent means of attempting to verify these estimates.

1) *Uranium purchases*. Through 1975, the Atomic Energy Commission (AEC) had acquired about 80 percent of the total uranium purchased in the United States since 1942. Through 1970 (the last year of AEC purchases), about 95 percent went to the government (*3*). Thus, it is not surprising that by 1970 the military had fissioned more than seven times as much uranium as the civilian sector (Table 1).

2) *Nuclear waste*. The announced inventory, I, of ^{90}Sr in the military high-level waste accumulated through 1975 was about 270 million curies (*4*). At a ^{90}Sr fission yield, Y, of 0.052 atom per fission (*5*) and 4.6×10^{19} atoms of ^{90}Sr per curie, K, we obtain a thermal energy

$$I \times K \times (2.9 \times 10^{-14} \text{ Btu/fission}) \times Y^{-1} \tag{1}$$

of about 6.9×10^{15} Btu's (6.9 quad). Considering that the original inventory has decayed (^{90}Sr half-life = 28 years) and that not all of the military spent fuel had been reprocessed by 1975, this must be a low estimate. It is significantly higher, however, than the estimates in Table 1, which total about 5.3 quad for military reactors.

3) *Krypton-85 in the atmosphere*. Essentially all the contained ^{85}Kr is released during fuel reprocessing as well as during atmospheric nuclear detonations. The total atmospheric inventory ($I \times K$) in 1970 has been estimated at about 1.0×10^{27} atoms (*6–8*). Since there are essentially no natural sources or sinks for this isotope (*7*) and Y is about 0.28 percent (*8*), Eq. 1 gives about 10 quad. Decay due to the 10.8-year half-life of ^{85}Kr would indicate that the original inventory was from 1.4 to 2.0 times higher (*6, 8*). This leads to a world production of 14 to 20 quad from nuclear power. The total U.S. fission energy production through 1969 (Table 1) is about 5.0 quad, corrected for the fusion component of detonations (*9*). This figure would imply, since some spent military and commercial fuel had not been reprocessed by 1970, that the U.S. nuclear production from all sources was less than 25 percent of the world total. This is conceivable but seems low because U.S. nuclear production is usually considered to be about half of the world total to date (*10*). The ^{90}Sr and ^{85}Kr calculations are in support of the conclusion that the reported military uses of uranium in Table 1 are low but probably by not more than a factor of 2.

The second inconsistency contained in the usual energy accounts results from the special method used to determine the energy contribution from nuclear power. Nuclear energy is normally counted as the thermal Btu's actually produced in the power plants. This practice is inconsistent with the bookkeeping used for other fuels. Oil, gas, and coal are counted as Btu's of fuel extracted from the earth, and losses during shipping, refining, and combustion are included. Uranium is difficult to count in this manner because no standard measure of energy content is available. The energy per pound of uranium depends on the reactor type, burnup, tails assay, and other variables. Time lags further complicate the accounting for uranium use. Uranium mined in a particular year may not be fissioned until many years later, and, by then, the technology and energy efficiency may be quite different. Therefore, like hydropower, the preconversion efficiency of the nuclear fuel cycle is not easily defined or calculated. However, it hardly seems accurate to assume, as is the case in present practice, that the uranium fuel cycle is 100 percent efficient to the point of heat generation. In addition, unlike hydropower, nuclear power will probably have an expanding energy role and there are several possible technologies to be considered. The lack of an energy efficiency measure for the nuclear fuel cycle will increasingly distort the view of our overall energy consumption.

Scoreboard for Reports. The acceptance rate for Reports during the last year has been about 25 percent. The number accepted has exceeded the number published and publication delay has increased to about 4 months. For the next few months, our acceptance rate will be about 15 percent, or 10 Reports per week.

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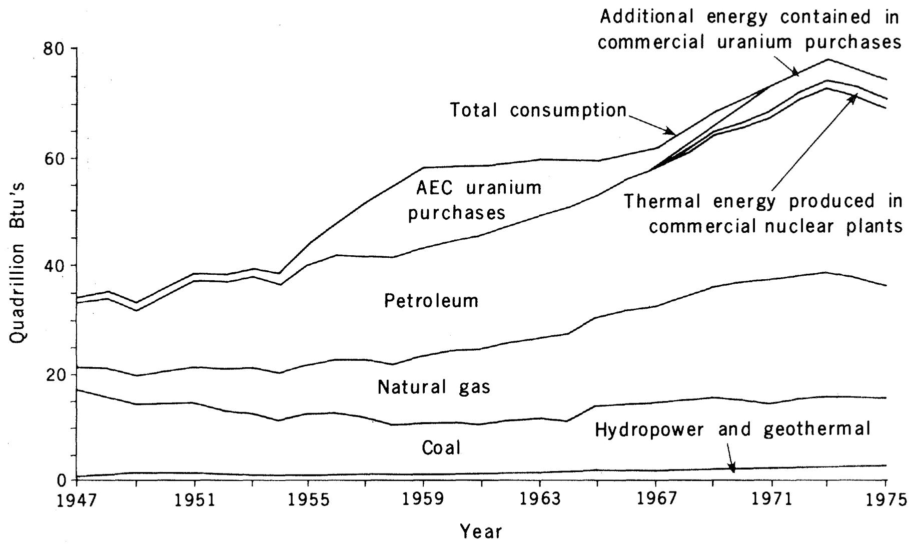

Fig. 1. Total U.S. energy consumption: uranium purchases from (3) were counted as 2.0×10^8 Btu's per pound of U_3O_8 in the year of purchase. Other data are from (2).

Table 1. Thermal energy produced by U.S. military and civilian uses of nuclear energy, 1945 through 1975. Not included are the U.S.S. *Savannah*, civilian and military experimental and research reactors, and small nuclear power units for remote or space applications.

Year	Plutonium production reactors*		Nuclear detonations†		Naval reactors‡		Commercial reactors	
	Power level [GW (thermal)]	Energy ($\times 10^{12}$ Btu's)	Number	Energy ($\times 10^{12}$ Btu's)	Capacity [GW (thermal)]	Energy ($\times 10^{12}$ Btu's)	Capacity [GW (thermal)]	Energy ($\times 10^{12}$ Btu's)
1945	0.5	15	3	0.2				
1946	1.1	35	2	0.2				
1947	1.7	50						
1948	2.3	70	3	0.4				
1949	2.9	85						
1950	3.5	105						
1951	4.1	125	16	2				
1952	4.7	140	10	42				
1953	5.3	160	11	1				
1954	5.9	175	6	180	0.055	0.8		
1955	6.5	195	15	0.8	0.055	0.8		
1956	6.5	195	14	60	0.055	0.8		
1957	6.5	195	28	1.6	0.15	2.0	0.375	1
1958	6.5	195	66	120	0.2	2.7	0.375	2
1959	6.5	195			0.45	6.6	0.375	2
1960	6.5	195			0.65	9.5	0.975	6
1961	6.5	195	12	0.8	2.4	36	1.38	18
1962	6.5	195	99	150	2.85	43	2.29	24
1963	6.5	195	34	6	3.25	49	2.69	34
1964	6.5	195	28	3.6	4.2	63	2.83	35
1965	5.6	170	28	3.8	4.4	66	2.89	38
1966	4.6	140	40	9.6	4.95	74	6.07	57
1967	4.6	140	28	6.4	5.6	84	9.02	80
1968	4.2	125	33	18	5.8	87	8.8	130
1969	3.3	100	28	17	6.3	95	12.44	146
1970	2.8	85	30	11	6.5	97	20.29	229
1971	2.3	70	11	22	6.9	103	27.15	404
1972	1.9	55	8	1.2	7.1	106	47.81	576
1973	1.9	55	9	4.6	8.65	129	66.19	888
1974	1.9	55	7	1.8	9.0	135	98.94	1202
1975	1.9	55	16	15	10.3	154	121.7	1652
Total (rounded)		4000	585	600		1300		5500

*Estimates of annual power levels through 1964 are from (7). For subsequent years, I determined the levels by prorating the maximum level achieved from 1955 through 1964 by the number of reactors still in service as reported in (*12*). The total capacity would be greater because the capacity factors are less than 100 percent. †One kiloton of TNT = 4×10^9 Btu's. All the annual totals of announced detonations and yields after 1963 are from (*13*). Yields before 1963 were often not announced and have been estimated from the data in (*9*, *13*, *14*). The data for the last half of 1975 are from (*15*). The energy was approximately equally divided between fission and fusion (*9*). Plowshare tests are included. ‡I determined the thermal power of the naval reactors by applying the reported efficiency of the nuclear-powered merchant ship *Savannah* in (*16*). I multiplied this figure, 3.64 MW (thermal) per 1000 shaft horsepower, by the horsepower estimates for U.S. nuclear warships in (*17*). I used a capacity factor of 50 percent to estimate the energy consumption.

One consequence of this lack is that nonfuel uses of uranium are not counted. This is inconsistent with the case for other energy sources where nonfuel consumption is accorded an energy content and charged against energy consumption [for example, oil used for asphalt and petrochemical stock (*2*)]. For uranium, the major nonfuel use is weapons manufacturing. There is no more reason to think that a pound of U_3O_8 that has been used to make a weapon will ever be used as a reactor fuel any more than that asphalt will be used in a boiler. At the least, it might be charged against the energy accounts as an energy opportunity cost.

As a rough first approximation only, an energy content can be assigned to uranium equivalent to its use in the most common U.S. nuclear fuel cycle (light-water reactor without plutonium recycle) (*11*). If, in the absence of declassified information about weapons production and uranium stockpiles, the energy is assigned to the energy accounts in the year in which the uranium is purchased, a marked change occurs in the usual picture of U.S. energy production. Figure 1 illustrates that, by this measure, in the years around 1960 the military consumed more nuclear energy than the whole country consumed as coal or natural gas. In these years the energy use of the AEC exceeded that of the residential, commercial, and transportation sectors and rivaled that of the industrial sector (*2*). Of course, some of this uranium was held in stockpiles and not used during the year of purchase. However, the year of purchase has been used here because adequate data on stockpiles are not found in the open literature.

We entered the Atomic Age on 2 December 1942. Yet no nuclear energy appears in the energy accounts until the first commercial power plant began operating in 1957. The AEC, in naval and plutonium production reactors as well as bombs, apparently fissioned at least 7 and perhaps 15 times as much uranium as was fissioned commercially before 1970. However, only the commercial use has been counted in the tabulations of energy consumption. The environmental, economic, political, and social changes wrought by the use of uranium have made the Atomic Age and are the products of the energy contained in uranium. Nearly all the uranium requirements and nearly all the global changes created by nuclear energy to date are due to military uses. The costs and benefits of these changes are even harder to determine and judge than those associated with more conventional uses of energy, but this is no excuse for omitting them from the accounts. Military consumption of nuclear energy directly, in detonations and reactors, and indirectly, in weapons manufacture, raises questions that are at least as vital to the world as those raised by other uses of energy.

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References and Notes

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Evolution of a Nitrogen Atmosphere on Titan

Abstract. *Photochemical calculations indicate that if NH_3 outgassed from Titan it should have been converted to a dense N_2 atmosphere during the lifetime of the satellite. A crucial step in the process involves a gas phase reaction of N_2H_4 with H. The most favorable conditions for this step would be the intermediate production of a CH_4-H_2 greenhouse capable of raising the gas temperature to 150°K. Subsequently about 20 bars of N_2 could have evolved. The pressure-induced opacity of 20 bars of N_2 should suffice to explain the recently measured 200°K surface temperature. Unlike the situation on Jupiter, NH_3 is not recycled on Titan by reactions involving N_2 or N_2H_4. This may explain the failure of recent attempts to detect NH_3 in the upper atmosphere of Titan.*

Hunten (*1*) first proposed that N_2 might be the dominant gas in the atmosphere of Titan. Ammonia may have been irreversibly converted (*1, 2*) to other nitrogen-bearing compounds such as N_2, N_2H_4, and CH_3NH_2. Recent measurements by Owen (*3*) place 30 cm-atm as the upper limit for NH_3 above the clouds on Titan.

We have investigated the photochemistry of NH_3 in the primordial Titan atmosphere and developed a model for the evolution of the atmosphere during geologic time. Our conclusion is that if NH_3 was available on Titan, a dense N_2 atmosphere of 14 to 19 bars at the present time is plausible. We have also estimated the amount of H_2 that would be present as a result of production in NH_3 photochemistry and loss by Jeans escape in the case of limiting flux.

We propose the following scenario. After cooling and solidification of Titan's surface, and once outgassing began, the atmosphere may have contained such gases as CH_4 and NH_3. These gases were photolyzed, and NH_3 was converted to other nitrogen-bearing compounds while CH_4 continued to build up in the atmosphere. Photolysis can convert some CH_4 to other species. On the basis of possible recapture by Titan of escaping hydrogen atoms, Strobel (*4*) has estimated that up to 60 percent of CH_4 may be recycled. Molecular hydrogen was also produced in the photolysis of these gases. Once the CH_4-H_2 surface pressure reached 0.1 bar, the greenhouse effect began to be important and the atmospheric temperature began to rise above the equilibrium value of 86°K. Calculations by Pollack (*5*) indicate that by the time the pressure of the CH_4-H_2 atmosphere reached 0.45 bar, the surface temperature would have been 150°K. Present-day spectroscopic observations place an upper limit on CH_4 much lower than the amount required for a greenhouse effect leading to a 150°K temperature. These observations, however, apply to CH_4 in the visible atmosphere above the clouds. The existence of a much larger CH_4 abundance below the clouds is entirely possible.

The photochemistry of NH_3 has been discussed in detail in the context of Jupiter in a recent paper by Atreya *et al.* (*6*). The photochemical scheme is shown in Fig. 1 and the relevant rate constants are given in Table 1. Photolysis of NH_3 in the range 160 to 230 nm leads to the formation of H and the radical NH_2. A fraction of NH_3 is recycled by the reaction of NH_2 with H (reaction R2). Reaction of NH_2 with itself (R3) forms hydrazine, N_2H_4. Assuming that N_2H_4 remains in the vapor phase, it undergoes photolysis in the same spectral range as NH_3 (R5) or reacts with H (R4). Both these processes produce the radical N_2H_3. Reactions of N_2H_3 with itself can lead to NH_3 (R8) or N_2H_4 and N_2 (R9). The recycling of NH_3 by the path R8, however, is insignificant compared to N_2 production by R9. The final products of this gas phase photochemistry are thus N_2 and H_2.

During the early phases of the evolution of the atmosphere, the NH_3 volume mixing ratio would have been determined by its saturation vapor pressure. The vapor pressure at 86°K is 1×10^{-6} mbar, at 100°K is 2×10^{-5} mbar, and at 120°K is 3×10^{-3} mbar. In any event, photolysis of NH_3 proceeded from the beginning, the altitude at which it predominantly occurred rising as the atmospheric temperature increased with the development of the CH_4-H_2 greenhouse. The photochemical cycle leading to N_2 may have terminated during the early history of the atmosphere with the formation of N_2H_4. For the range of N_2H_4 partial pressures prevailing during this period, N_2H_4 can condense at temperatures below 150°K. However, it is conceivable that the gas phase chemistry

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